ON THE FORMATION OF PULSES OF COHERENT RADIATION IN WEAKLY INVERTED MEDIA

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A change in the character of maser generation in a two-level system is found when the initial population inversion exceeds some threshold value equal to the square root of the total number of atoms. Above this threshold, the number of photons begins to grow exponentially with time and the pulse with short leading edge and broadened trailing edge is generated. In this work, we attempt to explain the nature of this threshold. Coherent pulse duration, estimated by its half-width, increases significantly with increasing inversion, if all other parameters are fixed and the absorption is neglected. The inclusion of the energy loss of photons leads to the fact that the duration of coherent pulse is almost constant with increasing inversion, at least well away from the threshold.

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INTRODUCTION

Description of physical phenomena based on the systems of partial differential equations, derived from the observations and experimental facts, often conceals from an investigator some essential features, especially in those cases, when the researchers do not expect to find anomalies and qualitative changes in the dynamics of systems in given range of variables and parameters. Namely such a case of unusual behavior of a two-level quantum system was found in attempting to separate a coherent component from the total radiation flow.

In the beginning of the past century, A. Einstein has proposed the model of two-level system, which has demonstrated the possibility of generation of both spontaneous and induced (stimulated) emission when the initial population inversion is sufficiently large [1]. Usually, the term spontaneous emission denotes the emission of oscillator (or other emitter) which not forced by external field of the same frequency. As for other influences on the characteristics of the spontaneous emission, there is nothing to say definitely. Although the dynamics of spontaneous processes usually shows a steady recurrence and invariance, there is evident [2] that the characteristics of the spontaneous processes can vary with change of environment. By induced or simulated emission is usually meant the emission produced because of an external field action on the emitting source at the radiation frequency.

There were difficulties in the quantum description with interpretation of the stimulated emission as coherent, where in contrast to the classical case it was impossible to say anything about the phases of the fields emitted by individual atoms and molecules. However, C. Townes believed that "… the energy delivered by the molecular systems has the same field distribution and frequency as the stimulating radiation and hence a constant (possibly zero) phase difference" [3].

If we assume, relying upon the results of the studies of fluctuation correlations in the laser radiation [4], that a stimulated emission has a high proportion of the coherent component, one can find a threshold of coherent radiation at a certain critical value of population inversion [5]. The specific feature of this threshold is that it follows from the condition that the initial value of the population inversion is equal to the square root of the total number of states. On the other hand, the change in the nature of the process near the threshold is evident, even without making any other assumptions. Above this threshold, the number of photons begins to grow exponentially with time. Herewith, below the threshold there no exponential growth.

It is known that at low levels of spontaneous component and far above the maser generation threshold the number of photons growths exponentially and the radiation is largely a coherent [6, 7]. The meaningful indicator of the collective character of stimulated emission is the so-called photon degeneracy, which is defined as the average photon number contained in a single mode of optical field (see, for example [8]). For the incoherent light, this parameter does not exceed unity, but for even the simplest He-Ne maser it reaches the value of 10^{12} as was shown in the early works (see [6]).

It is of interest to go further and analyze the consequences of consideration of the spontaneous emission as a random process (at least, in a homogeneous medium) and induced process as a coherent process. It is clear that the separation of total radiation into two category: the stimulated – coherent and spontaneous – random or incoherent will be idealized simplification. However, such separation may explain, at least qualitatively, the nature of the radiation emitted by two-level quantum system near to exposed threshold.

Another indirect proof of the existence of such a threshold is the following observation. The intensity of the spontaneous emission, which is non-synchronized (randomly distributed) over oscillators phases is known to be proportional to their number. The intensity of the coherent stimulated emission is proportional in turn to the square of the number of oscillators. It is easy to see that the exposed threshold corresponds to the case when the intensity of spontaneous and stimulated coherent radiation become equal.

In [5] we have shown that under these conditions the pulse of coherent radiation with a characteristic profile is formed when the initial population inversion slightly exceeds the threshold. The leading edge of the pulse due to the exponential growth of the field is very sharp due to the exponential growth of the field, and the trailing edge is rather broadened. Further overriding of the threshold, that is growing of the initial population inversion, results in the ratio of the trailing edge duration to the leading edge duration becomes greater. At large times the incoherent radiation dominates.

Because very small value of the initial population inversion can provide generation of pulses of coherent radiation, it is of interest to determine the shape of these pulses for different values of the initial population inversion levels and when the field energy absorption should be taken into account. These pulses can be easily detected in experiments. In addition, after experimental validation of this model, it will be possible to use these approaches for analysis of the cosmic radiation that might help explain such abundance of coherent radiation sources in space.

In this paper, we study the characteristics of the pulses of coherent radiation as a function of the initial inversion and absorption level in the system. The dynamics of the emission process in the simplified model is compared with the dynamics of change in the number of quanta in the traditional model, where the separation into coherent and incoherent components is not carried out.

1. TRADITIONAL DESCRIPTION OF TWO-LEVEL SYSTEM

Following to A. Einstein [1], a two-level system with transition frequency $\varepsilon_2 - \varepsilon_1 = \hbar\omega_{12}$ can be described by following set of equations:

$$\partial n_2 / \partial t = -(u_{21} + w_{21} \cdot N_k) \cdot n_2 + w_{12} \cdot N_k \cdot n_1 , \tag{1}$$
$$\partial n_1 / \partial t = -w_{12} \cdot N_k \cdot n_1 + (u_{21} + w_{21} \cdot N_k) \cdot n_2 ,$$

where the sum of level populations $n_1 + n_2 = N$ remains constant, $u_{21}n_2$ is the rate of change in the number density of atoms due to spontaneous emission. The rates of change in level population due to stimulated emission and absorption are $w_{21}N_k n_2$ and $w_{12}N_k n_1$ correspodingly. The number of quanta N_k on the transition frequency ω_k is governed by the equation

$$\frac{\partial N_k}{\partial t} = (u_{21} + w_{21} \cdot N_k) \cdot n_2 - (w_{12} \cdot N_k) \cdot n_1 . \tag{2}$$

The losses of energy in active media are caused mainly by radiation outcome from a resonator. These radiative losses can be calculated by imposing the correct boundary conditions on the field. Thus, they can be estimated in rather common form with the following parameter:

$$\delta = \oiint_S \frac{\partial\omega}{\partial\vec{k}} \frac{1}{4\pi} \vec{E} \times \vec{H} ds \Bigg/ \iiint_V \frac{\partial[\omega\varepsilon(\omega,\vec{k})]}{\partial\omega} \times \times \frac{1}{8\pi} (|\vec{E}|^2 + |\vec{H}|^2) dv, \tag{3}$$

i.e. as the ratio of the energy flow passing through the resonator mirrors to the total field energy within resonator. It is important, that the characteristic size of the resonator L should be much less than the characteristic time of field variation $\tau \sim |\vec{E}|^2 (\partial |\vec{E}|^2 / \partial t)^{-1}$ multiplied by the group velocity of oscillations $|\partial\omega / \partial\vec{k}|$. In this case the radiative losses through the mirrors can be replaces by distributed losses whithin the resonator volume. The threshold of instability leading to exponentiol growth of coherent emission in this case is defined by condition $\mu_0 > \mu_{TH1}$ (see, for example [6], where

$$\mu_{TH1} = \delta / w_{21} . \tag{4}$$

Equations (1) - (2) can be rewritten in the form

$$\partial n_2 / \partial \tau = -n_2 - \mu \cdot N_k , \tag{5}$$
$$\partial \mu / \partial \tau = -2n_2 - 2\mu \cdot N_k , \tag{6}$$
$$\partial N_k / \partial \tau = n_2 + \mu \cdot N_k , \tag{7}$$

where $\tau = w_{21} \cdot t$, $u_{21} = w_{21} = w_{12}$. Since the purpose of this work is to find the threshold of the initial population inversion, which starts the exponential growth of the number of emitted quanta, we will restrict our consideration by the case $\mu = n_2 - n_1 << n_1, n_2$. It follows from Eqs. (5) - (7) that $N_k = N_{k0} + (\mu_0 - \mu)/2 \approx (\mu_0 - \mu)/2$, and at large times $n_{2st} \approx N/2 = -\mu_{st} \cdot (\mu_0 - \mu_{st})/2$, where $\mu_0 = \mu(\tau = 0)$, $N_{k0} = N_k(\tau = 0)$. Hence, we find the stationary value of the inversion

$$\mu_{st} = (\mu_0 / 2) - \sqrt{(\mu_0 / 2)^2 + N} . \tag{8}$$

Two cases are of interest. When the initial population inversion is sufficiently large $(\mu_0 / 2)^2 >> N$, it rapidly decreases to its steady-state value $\mu \to \mu_{st1} = -(N / \mu_0)$ with $|\mu_{st1}| << \mu_0$.The number of quanta at this growths exponentially and asymptotically tends to a stationary level $N_k \to N_{kst1} = \mu_0 / 2$. It is obviously that in this case the stimulated emission dominates (the second terms in r.h.s. of Eqs. (5) - (7)).

The second case of interest corresponds to relatively small initial inversion $(\mu_0 / 2)^2 << N$. Here, μ tends to its stationary value $\mu \to \mu_{st} = -(N)^{1/2}$, where $|\mu_{st}| > \mu_0$, and the number of quanta reaches the limit $N_k \to N_{kst2} = N^{1/2}$.

If the spontaneous emission only dominated (the first terms on the r.h.s. of Eqs.(5) - (7)), the characteristic time to reach the steady-state number of photons will be of the order of $\Delta\tau \sim \tau_m = \mu_0 / N > \mu_0^{-1}$ in the first case and $\Delta\tau \sim 1/\sqrt{N} < \mu_0^{-1}$ in the second case, where μ_0^{-1} is the characteristic time of exponential growth of the number of photons in the first case. This means that the exponential growth of the number of photons in the second case is suppressed and the role of the second terms in r.h.s. of Eqs. (5) - (6) comes to stabilize the number of particles and the inversion level due to the absorption process.

Thus, it is clear that the scenario of the process changes, if the initial value of the inversion μ_0 is more or less thana threshold value [5]:

$$\mu_{TH2} = 2N^{1/2} . \tag{9}$$

The suppression of the exponential growth of the number of photons when $\mu_0 < \mu_{TH2} = 2N^{1/2}$ demonstrates not only the changes in scenario of the process, but it suggests that the stimulated emissionis suppressed by preferential growth of spontaneous emission. Indeed, the first term in r.h.s. of Eqs. (5) - (7), which is responsible for the spontaneous emission, reduces in version to zero in a very short time $\tau < 1/\mu_{TH2}$, thus excluding the possibility of exponential growth of the number of photons, which is characteristic for the induced processes.

It is useful, at least qualitatively, to examine the nature of changes in emission characteristics of an inverted system near the threshold μ_{TH2}. It should be expected also other specific features in the radiation nature, including the formation of a short pulse of coherent radiation against the background of incoherent field [5].

2. QUALITATIVE MODEL OF TWO-LEVEL SYSTEM

First of all, in order to understand the further, it should be remembered that the oscillator emits under the action of an external coherent field with the same frequency and phase as the stimulating field, that is, the external radiation and radiation of the oscillator stimulated by it occur to be coherent [6, 7]. Moreover, the greater intensity of the coherent component of the external field, the more energy the oscillator loses per unit time by radiation. On the other side, the spontaneous emission is the process independent of the external radiation field and incoherent, at least for a uniform distribution of emitters.

Neglecting the stage when the number of photons is saturated, we can at least qualitatively assume that the terms in r.h.s. of Eq. (1) - (2) proportional to N_k correspond to the coherent processes, as well as the photons which number N_k is incorporated in these terms will be assumed coherent. With these general principles in mind, we expand the total number of photons into two components $N_k = N_k^{(incoh)} + N_k^{(coh)}$ and rewrite Eqs. (2)-(3) as follows [11]

$$\partial n_2 / \partial t = +w_{12} \cdot N_k^{(coh)} \cdot n_1 - (u_{21} + w_{21} \cdot N_k^{(coh)}) \cdot n_2, \quad (10)$$

$$\partial n_1 / \partial t = -w_{12} \cdot N_k^{(coh)} \cdot n_1 + (u_{21} + w_{21} \cdot N_k^{(coh)}) \cdot n_2, \quad (11)$$

$$\partial N_k^{(incoh)} / \partial t = u_{21} \cdot n_2, \quad (12)$$

$$\partial N_k^{(coh)} / \partial t = w_{21} \cdot N_k \cdot n_2 - w_{12} \cdot N_k \cdot n_1. \quad (13)$$

Assuming $u_{21} = w_{21} = w_{12}$ and $n_2 = (N+\mu)/2$, we obtain

$$\partial n_2 / \partial \tau = -n_2 - \mu \cdot N_k^{(coh)}, \quad (14)$$

$$\partial \mu / \partial \tau = -2n_2 - 2\mu \cdot N_k^{(coh)}, \quad (15)$$

$$\partial N_k^{(incoh)} / \partial \tau = n_2 \quad (16)$$

$$\partial N_k^{(coh)} / \partial \tau = \mu \cdot N_k^{(coh)}, \quad (17)$$

where $N = n_1 + n_2$ is a total number of emitters.

Let compare the dynamics of the processes described by Eqs. (14) - (17) and by Eqs. (5) - (7). In order to do this, we represent themas shown in Table:

The modelling set of equations with separation of quanta into coherent and incoherent sorts	
$\partial \mathrm{M} / \partial T = -N_0 - 2\mathrm{M} \cdot \mathrm{N}_c$,	(18)
$\partial \mathrm{N}_{inc} / \partial T = N_0 - \theta \cdot \mathrm{N}_{inc}$,	(19)
$\partial \mathrm{N}_c / \partial T = \mathrm{M} \cdot \mathrm{N}_c - \theta \cdot \mathrm{N}_c$.	(20)
Traditional set of equation	
$\partial \mathrm{M}_1 / \partial T = -2n_{21} - 2\mathrm{M}_1 \cdot \mathrm{N}_1$,	(21)
$\partial \mathrm{N}_1 / \partial T = n_{21} + \mathrm{M}_1 \cdot \mathrm{N}_1 - \theta \cdot \mathrm{N}_1$.	(22)

where $\mathrm{N}_{inc} = N_k^{(incoh)} / \mu_0$, $\mathrm{N}_c = N_k^{(coh)} / \mu_0$, $\mathrm{M} = \mu / \mu_0$, $\mathrm{M} = \mathrm{M}_1 = \mu / \mu_0$ $T = w_{21} \cdot \mu_0 \cdot t = \mu_0 \cdot \tau$ $\mathrm{N}_1 = N_k / \mu_0$. The only free parameter convenient for the analysis is $N_0 = N / \mu_0^2$. For correct comparison, we assume that the total number of real states is $N = n_1 + n_2 = 10^{12}$, and the threshold inversion is $\mu_{0th} = \sqrt{N} = 10^6$. Transition to a unified time scale will be carried out as follows $T = \tau \cdot \mu_0$, where T is time for each case. Let choose the following initial values

$$\mathrm{M}(T=0) = \mathrm{M}_1(T=0) = 1,$$

$$\mathrm{N}_{inc}(T=0) = \mathrm{N}_{inc} / \mu_0 = 3 \cdot 10^4 / \mu_0,$$

$$\mathrm{N}_c(T=0) = \mathrm{N}_c / \mu_0 = 3 \cdot 10^4 / \mu_0,$$

$$\mathrm{N}_1(T=0) = \mathrm{N}_k / \mu_0 = 3 \cdot 10^4 / \mu_0.$$

The radiation losses are taking into account by the term $\theta = \delta / \mu_0$, where δ is defined in (3).

Fig. 1 demonstrates a change in dynamics of the process with increase in the starting population inversion (9) simulated by Eqs. (21) - (22), where $N_0 \subset (30...0.01)$.

The attention should be given to a change in the rate of emitted quanta with crossing of the threshold (9). For greater values of the initial inversion, the stimulated emission begins to prevail and the regime of exponential growth in the number of quanta becomes more pronounced.

In the absence of radiative losses, the simulation of Eqs. (18) - (20) shows that after the coherent pulse drops, the spontaneous emission continues to increase. Within framework of the traditional model (21) - (22), absorption restricts the growth of the number of quanta and radiation intensity tends to a stationary level.

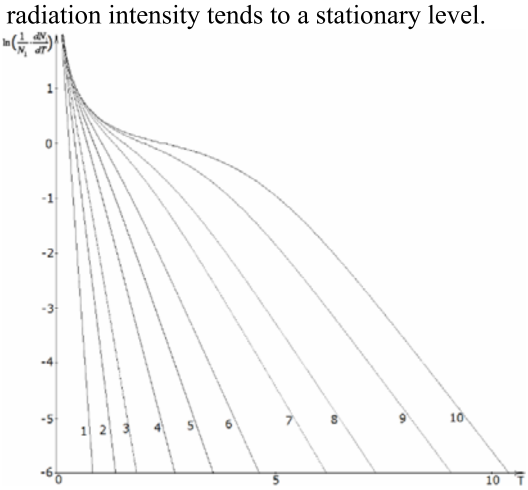

Fig. 1. Evolution of the value $\ln(dN_1/N_1 dT)$ *for different* $N_0 = (n_1+n_2)/(n_2-n_1)^2$ *: 1)* $N_0 = 30$ *; 2)* $N_0 = 10$ *; 3)* $N_0 = 5$ *; 4)* $N_0 = 2$ *; 5)* $N_0 = 1$ *; 6)* $N_0 = 0.5$ *; 7)* $N_0 = 0.2$ *; 8)* $N_0 = 0.1$ *; 9)* $N_0 = 0.03$

However, comparing the dynamics of the processes it can be understood that after the amplitude of the coherent pulse decreases, the spontaneous emission becames dominant. That is, attimes exceeding the duration of the coherent pulse the incoherent radiation prevails.

The absorption of photons suppresses the generation, so we choose relatively lowlevel of energy loss, that is $\delta = 2 \cdot 10^5$ and $\delta = 4 \cdot 10^5$. The generation process in this case keeps the same features, but the absorption limits the lifetime of the generation and the differences between two models areless pronounced.

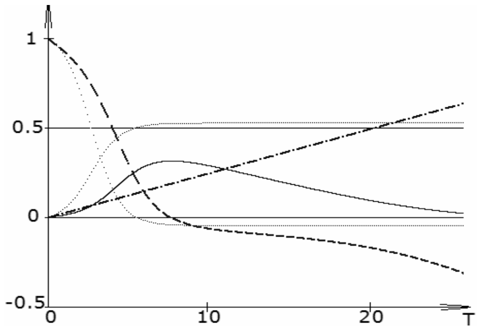

Fig. 2. Evolution of M_1 *and* N_1 *(dot line),* M *(dash line),* N_c *and* N_{inc} *(solid and dash-dot line correspondingly) in lossless case (* $\theta = 0$ *) and* $N_0 = N/\mu^2_0 = 0.05$

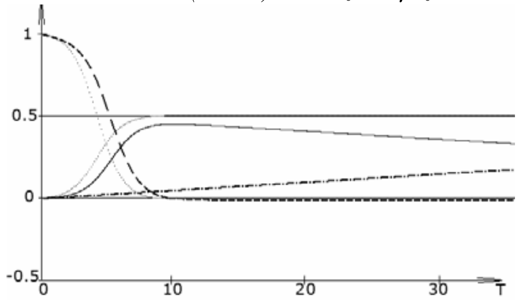

Fig. 3. Evolution of M_1 *and* N_1 *(dot line),* M *(dash line),* N_c *and* N_{inc} *(solid and dash-dot line correspondingly) for lossless case (* $\theta = 0$ *) and* $N_0 = N/\mu_0^2 = 0.01$

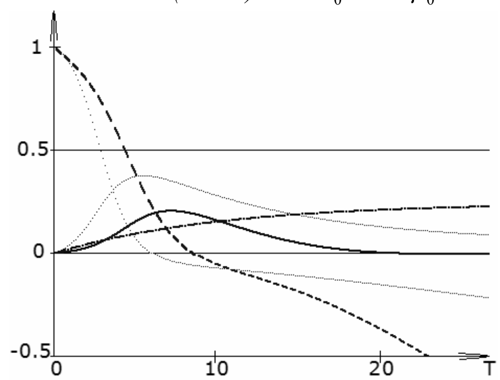

Fig. 4. Evolution of M_1 *and* N_1 *(dot line),* M *(dash line),* N_c *and* N_{inc} *(solid and dash-dot line correspondingly) with absorption (* $\delta = 2 \cdot 10^5$ *,* $\theta = \delta/\mu_0 = 0.045$ *) and* $N_0 = N/\mu_0^2 = 0.05$

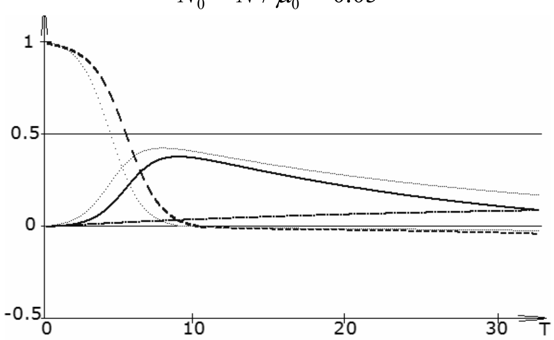

Fig. 5. Evolution of M_1 *and* N_1 *(dot line),* M *(dash line),* N_c *and* N_{inc} *(solid and dash-dot line correspondingly) with absorption (* $\delta = 4 \cdot 10^5$*,* $\theta = \delta/\mu_0 = 0.04$ *) and* $N_0 = N/\mu_0^2 = 0.01$

Now, let discuss the quantitative characteristics of the coherent pulse. Figs. 6 and 7 demonstrate the shape of the coherent pulse in lossless case and in presence of absorption for different initial value of the population inversion.

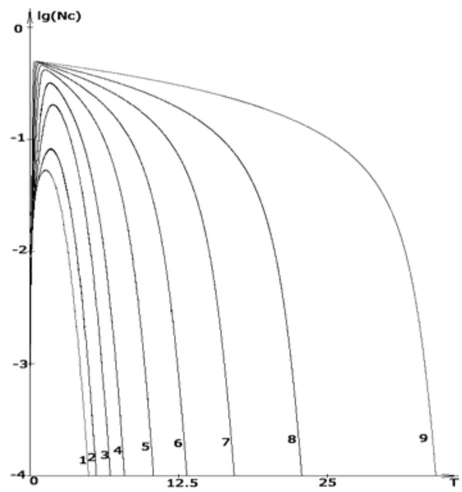

Fig. 6. Evolution of coherent pulse shape in absence of absorption ($\theta = 0$ *) for different values of initial population inversion 1)* $\mu_0 = \sqrt{2} \cdot 10^6$ *; 2)* $2 \cdot 10^6$ *; 3)* $\sqrt{10} \cdot 10^6$ *; 4)* $\sqrt{20} \cdot 10^6$ *; 5)* $\sqrt{50} \cdot 10^6$ *; 6)* 10^7 *; 7)* $\sqrt{2} \cdot 10^7$ *; 8)* $2 \cdot 10^7$ *; 9)* $\sqrt{10} \cdot 10^7$

Note the fact that in the case of a fixed finite level of loss, the shape and duration of the coherentpulsedoes not change even when the population inversion level increases significantly. Thus, the formation of the leading edge of the pulse is determined by the initial inversion level, the duration of its trailing edge is determined mostly by the rate of radiative loss.

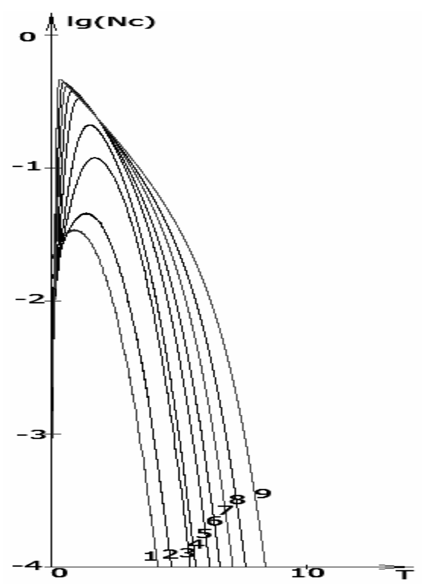

Fig. 7. Evolution of coherent pulse shape in presence of absorption ($\delta = 4 \cdot 10^5$ *) for different values of initial population inversion 1)* $\mu_0 = \sqrt{2} \cdot 10^6$ *; 2)* $2 \cdot 10^6$ *; 3)* $\sqrt{10} \cdot 10^6$ *; 4)* $\sqrt{20} \cdot 10^6$ *; 5)* $\sqrt{50} \cdot 10^6$ *; 6)* 10^7 *; 7)* $\sqrt{2} \cdot 10^7$ *; 8)* $2 \cdot 10^7$ *; 9)* $\sqrt{10} \cdot 10^7$

CONCLUSIONS

The threshold of coherent emission generation, discussed in this paper, corresponds to the case when the intensity of spontaneous and stimulated coherent radiation become equal. The stimulated emission in this case can be considered as completely coherent or as a set of narrow wave packets of coherent radiation. When the initial population inversion crosses the threshold (9), the process of generation undergoes qualitative changes. The excess of the threshold (9) leads to an exponential growth in the number of quanta. If we make the assumption that the stimulated emission is mainly coherent, the nature of this threshold can be explained as follows: generation of coherent radiation begins only after crossing of this threshold. In this work, we have tried to develop a qualitative model of this process.

It follows from results of numerical simulation that the number of coherent quanta tends to $\mu_0/2$ with increase of the initial population inversion in agree with the theory of super radiance [9 - 11]. If we fix all parameters except the inversion, the duration of the coherent pulse estimated by its half-width significantly increases with increasing initial inversion in the absence of absorption. The foregoing estimates of the characteristic times of the process are confirmed by numerical calculations. For relatively small inversion levels $\sqrt{N} \ll \mu_0 \ll N$ the coherent emission is always presents as a rather short pulse with duration of $\tau \sim (\mu_0/N)$. At large times $\tau > (\mu_0/N)$ the incoherent radiation dominates. Since the model (18) - (20) doesn't take into account absorption of the incoherent radiation, it becomes inapplicable after this time. It is important to note that the time when the total number of photons reaches the steady state in the model (21) - (22) after exceeding the threshold (9) is comparable with the time when the number of spontaneous photons achieves the same values $\Delta\tau \sim \tau_m = \mu_0/N$ in the model (18) - (20).

If the absorption is taken into account, even a small, the coherent pulse duration remains almost unchanged with an increase in the population inversion, at least far enough above the threshold. The ratio of the pulse-trailing edge duration to the pulse-leading edge duration (the latter, by the way, is inversely proportional to the initial inversion) is growing with increasing of the initial inversion. The duplication of absorption reduces the pulse duration by half. In an absorbing medium and when with significant overriding of the threshold (9), the difference between the traditional model and our qualitative description become insignificant.

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О ВОЗМОЖНОСТИ ФОРМИРОВАНИЯ ИМПУЛЬСОВ КОГЕРЕНТНОГО ИЗЛУЧЕНИЯ В СЛАБОИНВЕРСНЫХ СРЕДАХ

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Обнаружено изменение характера процесса генерации излучения в двухуровневой системе при превышении начальной инверсии заселенностей величины, равной корню квадратному из полного числа состояний. При превышении этого порога число квантов начинает расти экспоненциально со временем. Сделана попытка пояснить природу этого порога: при его превышении возникает генерация когерентного излучения в виде импульсов с коротким передним фронтом и протяженным задним фронтом. Если все параметры, кроме инверсии, зафиксировать, то с ростом инверсии в отсутствие поглощения длительность когерентного импульса, оцененная по его полуширине, заметно увеличивается. Учет потерь энергии квантов приводит к тому, что длительность когерентного импульса практически не изменяется при росте инверсии, по крайней мере, достаточно далеко от порога.

ПРО МОЖЛИВІСТЬ ФОРМУВАННЯ ІМПУЛЬСІВ КОГЕРЕНТНОГО ВИПРОМІНЮВАННЯ В СЛАБОІНВЕРСНИХ СЕРЕДОВИЩАХ

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Виявлено зміну характеру процесу генерації випромінювання в дворівневій системі при перевищенні початкової інверсії заселеності величини, що дорівнює кореню квадратному з повного числа станів. При перевищенні цього порога число квантів починає рости з часом за експонентою. Зроблена спроба пояснити природу цього порога: при його перевищенні виникає генерація когерентного випромінювання у вигляді імпульсів з коротким переднім фронтом і протяжним заднім фронтом. Якщо всі параметри, окрім інверсії, зафіксувати, то з подальшим ростом інверсії при відсутності поглинання тривалість когерентного імпульсу, оцінена за його напівшириною, помітно збільшується. Урахування втрат енергії квантів призводить до того, що тривалість когерентного імпульсу практично не змінюється при зростанні інверсії, принаймні, досить далеко від порога.